INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1990-91

Robert F. Stengel
Department of Mechanical and Aerospace Engineering
Princeton University
Princeton, New Jersey 08544

SUMMARY OF RESEARCH

The Air Transportation Technology Program at Princeton University, a program emphasizing graduate and undergraduate student research, proceeded along six avenues during the past year:

- Microburst Hazards to Aircraft
- Intelligent Failure-Tolerant Control
- Computer-Aided Heuristics for Piloted Flight
- Stochastic Robustness of Flight Control Systems
- Neural Networks for Flight Control
- Computer-Aided Control System Design

This research has resulted in a number of publications, including a thesis, archival papers, and conference papers. An annotated bibliography of publications that appeared between June, 1990 and June, 1991 appears at the end of this report. The research that these papers describe was supported in whole or in part by the Joint University Program, including work that was completed prior to the reporting period.

Severe downdrafts and resulting high velocity outflows caused by microbursts present a significant hazard to aircraft on takeoff and final approach. *Microbursts*, which are often associated with thunderstorm activity, also can occur in the vicinity of dissipating convective clouds that produce no rainfall at ground level. Microburst encounter is a rare but extremely dangerous phenomenon that accounts for one or two air carrier accidents and numerous general aviation accidents each year (on average). Conditions are such that an aircraft's performance envelope may be inadequate for safe penetration unless optimal control strategies are known and applied.

Our current wind shear research focuses on avoiding wind shear during transport aircraft operations, as well as on developing cockpit strategies for wind shear recovery. Graduate student Alex Stratton is developing an expert system for wind shear avoidance that extends the FAA Microburst Windshear Guidelines to account for temporal and spatial variations in the evidence that wind shear is present [1,2]. The approach being taken is to develop a Bayesian Belief Network that relates information gathered from many sources to determine the probability of encountering a microburst on the intended flight path. Our principal objectives are to develop methods for assessing the likelihood of wind shear encounter (based on real-time information in the cockpit), for deciding what flight path to pursue (e.g., abort, go-around, normal climbout, or glide slope), and for using the aircraft's full potential to combat wind shear. This study requires the definition of deterministic and statistical techniques for fusing internal and external information, for making "go/no-go" decisions, and for generating commands to the aircraft's autopilot and flight directors in automatic and manually controlled flight.

A number of graduate students have developed a fixed-base cockpit simulator for microburst studies, and graduate student Sandeep Mulgund has begun to use the simulator to determine the feasibility of target-pitch-angle (TPA) guidance for propellor-driven commuter-type aircraft. The simulation incorporates a cockpit station with manual input devices, a graphical display of instruments, and an out-the-window view. Currently the simulator is programmed to simulate a twin-jet transport aircraft and a twin-engine general aviation airplane. Preliminary results compare TPA guidance with an exact optimal control history, and they show the significant differences between best target pitch angles for head-tailwind shear and downdraft encounters. (Although the best single angle of attack for wind shear encounter is essentially the same for equivalent horizontal shears and vertical downdrafts, the corresponding pitch angles are decidedly different.) Graduate student Darin Spilman has used the simulator to conduct a preliminary analysis of an encounter of the twin-jet transport with an intense wind "rotor" capable of rolling the aircraft to inverted attitude, and he will examine effects of unsteady aerodynamics and heavy rain in his future research. Prior research on optimal flight paths conducted by Mark Psiaki is documented in [3].

Undetected system failures and/or inadequately defined recovery procedures have contributed to numerous air carrier incidents and accidents. The infamous DC-10 accident at Chicago's O'Hare Airport, in which loss of an engine pod, subsequent loss of subsystems, and asymmetric wing stall led to disaster, provides a prototype for the kind of tragedy that could be averted

by intelligent, failure-tolerant flight control systems. A survey of related considerations and control design methods is contained in [4].

Helping a pilot make quick decisions under high workload conditions is important for aircraft missions of all types. In research principally supported by an Army/Navy grant but reported at numerous quarterly reviews of the Joint University Program, Brenda Belkin developed an expert system of expert systems called AUTOCREW. In her M.S.E. thesis, Ms. Belkin used the paradigm of a hypothetical aircraft crew to facilitate the assignment of tasks, rules, and data within parallel knowledge bases. Ms. Belkin was the recipient of the 1990 William E. Jackson Award of the Radio Technical Commission for Aeronautics for her thesis, and the research is further presented in [5-7].

Control system robustness is defined as the ability to maintain satisfactory stability or performance characteristics in the presence of all conceivable system parameter variations. While assured robustness may be viewed as an alternative to gain adaptation or scheduling to accommodate known parameter variations, more often it is seen as protection against uncertainties in plant specification. Consequently, a statistical description of control system robustness is consistent with what may be known about the structure and parameters of the plant's dynamic model. Graduate student Laura Ryan Ray completed her Ph.D. thesis on this topic [8] and co-authored a number of related papers [9-11]. Chris Marrison currently is applying *Stochastic Robustness Analysis* to ten controllers designed in response to the 1990 American Control Conference Benchmark Control Problem challenge [12]. His results show the marked disparity in control systems designed by various methods, not only in their nominal performance but in the likelihood that they will achieve design goals.

There is growing interest in the use of neural networks for computational decision-making and control, brought about by the advent of small, fast, inexpensive computers. The neural network paradigm offers a potentially attractive structure for flight control systems that adapt to changing flight conditions and system failures, but much is to be learned about the practicality of such an approach. Graduate student Dennis Linse has begun to examine this potential. Current research focuses on the application of the feed-forward back-propagation network to identifying and modeling the nonlinear aerodynamics of a twin-jet transport aircraft [13].

Graduate student Subrata Sircar has begun to examine concepts for the next generation of computer-aided flight control system design through development of a comprehensive computer program called *FlightCAD*. The

program contains a variety of modeling, synthesis, simulation, and evaluation alternatives, and it will be applied to the design of flight control logic for the *1991 AIAA Controls Design Challenge.* It is organized around a desktop metaphor that takes advantage of unique capabilities of the NeXT Computer. A direct digital synthesis technique is employed; it will produce a proportional-integral-filter controller with scheduled linear-quadratic-Gaussian gains. Tight following of pilot commands will be assured by a forward-loop command generator tracker, and the controller will be sufficiently robust to account for specified levels of parameter uncertainty. A principal feature of the control design package is the enhanced ability to iterate and search during the modeling, design, and analysis process.

ANNOTATED BIBLIOGRAPHY OF 1990-91 PUBLICATIONS

1. Stratton, D.A., and Stengel, R., Probabilistic Reasoning for Intelligent Wind Shear Avoidance, *Proceedings of the 1990 AIAA Guidance, Navigation & Control Conference*, Portland, OR, Aug 1990, pp. 1099-1107.*

Avoiding severe wind shear challenges the ability of flight crews, as it involves assessing risk from uncertain evidence. A computerized intelligent cockpit aid can increase flight crew awareness of wind shear, improving avoidance decisions. A primary task in the development of such a cockpit aid is providing a means of assessing risk from evidence of wind shear from sources with varying reliability. The Federal Aviation Administration's Windshear Training Aid provides guidelines for assessing the risk of wind shear encounter from meteorological evidence. Use of these guidelines in the cockpit is complicated by uncertainty surrounding meteorological knowledge of wind shear. Bayesian network representation is discussed as a means of modeling this uncertain knowledge in a computer. A probabilistic model of the Windshear Training Aid guidelines using Bayesian network representation is presented. This model combines evidence from sources of varying reliability and incorporates results from meteorological studies of wind shear. The probabilistic model can provide flight crews with meaningful estimates of risk to aid their decisions, using evidence from a variety of sources and a base of meteorological knowledge.

2. Stratton, D.A., and Stengel, R., Stochastic Prediction Techniques for Wind Shear Hazard Assessment, *Proceedings of the 29th IEEE Conference on Decision and Control*, Honolulu, Dec 1990, pp. 702-707.*

The threat of low-altitude wind shear has prompted development of aircraft-based sensors that measure winds directly on the aircraft's intended flight path. Measurements from these devices are subject to turbulence inputs and measurement error, as well as to the underlying wind profile. In this paper, stochastic estimators are developed to process on-board doppler sensor measurements, producing optimal estimates of the winds along the path. A stochastic prediction technique is described to predict the hazard to the aircraft from the estimates as well as the level of uncertainty of the hazard prediction. The stochastic prediction technique is demonstrated in a simulated microburst wind shear environment. Use of the technique in a decision-making process is discussed.

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* Conference Paper

3. Psiaki, M., and Stengel, R., Optimal Aircraft Performance During Microburst Encounter, *J. Guidance, Control, and Dynamics*, Vol. 14, No. 2, Mar-Apr 1991, pp. 440-446.**

The effects of microburst characteristics on the optimal penetration performance of jet transport and general aviation aircraft are presented. The purpose is to determine the best possible performance that can be achieved in a broad range of microbursts. A secondary goal is to illustrate good strategies for dealing with a range of microbursts during takeoff and landing. Over 1100 optimal trajectories were computed for two aircraft types flying through idealized microbursts using a Successive Quadratic Programs trajectory optimization algorithm. Contours of safety metrics are plotted as functions of the length scales, magnitudes, and locations of horizontal wind shears and vertical downdrafts. These performance contours show three length-scale regimes for optimal microburst penetration. At short length scales, hazards usually associated with gustiness predominate. At intermediate length scales, a degraded ability to maintain flight path and/or vertical velocity poses the most serious threat. At very long microburst length scales, excessive touchdown velocities may result. The ability to transit a microburst successfully also varies strongly with microburst location. The results show that both aircraft types could penetrate some very severe microbursts if optimal control histories were followed. Nevertheless, these control strategies assume perfect prior knowledge of the wind, and practical limits to successful encounter with real-time control capabilities would be lower. The optimally controlled jet transport can successfully penetrate higher intensity microbursts than can the general aviation aircraft.

4. Stengel,. R., Intelligent Failure-Tolerant Control, *Proceedings of the 5th IEEE International Symposium on Intelligent Control*, Philadelphia, Sept 1990, pp. 548-557. (To appear in the *IEEE Control Systems Magazine.*)*

An overview of failure-tolerant control is presented, beginning with robust control, progressing through parallel and analytical redundancy, and ending with rule-based systems and artificial neural networks. By design or implementation, failure-tolerant control systems <u>are</u> "intelligent" systems. All failure-tolerant systems require some degree of robustness to protect against catastrophic failure; failure tolerance often can be improved by adaptivity in decision-making and control, as well as by redundancy in measurement and actuation. Reliability, maintainability, and survivability can be

** Archival Paper

enhanced by failure tolerance, although each objective poses different goals for control system design. Artificial intelligence concepts are helpful for integrating and codifying failure-tolerant control systems, not as alternatives but as adjuncts to conventional design methods.

5. Belkin, B., and Stengel, R., Quantitative Knowledge Acquisition for Expert Systems, *Engineering Applications of Artificial Intelligence*, Vol. 3, No. 4, Dec 1990, pp. 271-281.**

A common problem in the design of expert systems is the definition of rules from empirical data obtained in system operation or simulation. While it is relatively easy to collect numerical data and to log the comments of human operators engaged in experiments, generalizing such information to a set of rules has not previously been a straightforward task. This paper presents a statistical method for generating the needed rule base from numerical data, motivated by an example based on vehicle navigation with multiple sensors. The specific objective is to design an expert system that selects a satisfactory suite of measurements from a dissimilar, redundant set, given an arbitrary navigation geometry and possible sensor failures.

6. Belkin, B., and Stengel, R., Knowledge Acquisition for Expert Systems Using Statistical Methods, *Knowledge Based System Applications for Guidance and Control*, AGARD CP-474, Madrid, Sept 1990, pp. 25-1 to 25-17.**

This paper expands on the previous paper, describing the systematic development of a Navigation Sensor Management (NSM) Expert System from Kalman Filter covariance data. The development method consists of the two statistical techniques: *Analysis of Variance (ANOVA)* and the *ID3 algorithm*. The ANOVA technique indicates whether variation of a problem parameter gives *statistically* different covariance results, and the ID3 algorithm identifies the *relationships* between the problem parameters using probabilistic knowledge extracted from a simulation example set. ANOVA results show that statistically different position accuracies are obtained when different navaids are used, the number of navigation aids is changed, the trajectory is varied, or the performance history is altered. By indicating that these four factors significantly affect the decision metric, an appropriate parameter framework was designed, and a simulation example base was created. The example base contained over 900 training examples from nearly 300 simulations. The ID3 algorithm was used to determine the NSM Expert's classification "rules" in the form of *decision trees*. The performance of these decision trees was assessed on two arbitrary trajectories, and

the performance results are presented using a predictive metric. The test trajectories used to evaluate the system's performance show that the NSM Expert adapts to new situations and provides reasonable estimates of the expected hybrid performance. The results also show how the NSM Expert chooses optimal or next-best navigation strategies when limited computational resources are available; in simple cases, its solutions are commensurate with the designer's intuition.

7. Belkin, B., and Stengel, R., Systematic Methods for Knowledge Acquisition and Expert System Development, *Proceedings of the 29th IEEE Conference on Decision and Control*, Honolulu, Dec 1990, pp. 2191-2197 (To appear in *IEEE Systems Magazine*).*

Nine interacting rule-based systems collectively called AUTOCREW were designed to automate functions and decisions associated with a combat aircraft's subsystems. The organization of tasks within each system is described; performance metrics were developed to evaluate the workload of each rule base and to assess the cooperation between rule bases. Each AUTOCREW subsystem is composed of several expert systems that perform specific tasks. The NAVIGATOR was analyzed in detail to understand the difficulties involved in designing the system and to identify the tools and methodologies that ease development.

8. Ray, L.R., Stochastic Robustness of Linear Multivariable Control Systems: Towards Comprehensive Robustness Analysis, Ph.D. Thesis, Princeton University, Princeton, January, 1991.+

Stochastic robustness, a simple numerical procedure for estimating the stability and performance effects of parameter uncertainty in multivariable, linear, time-invariant control systems, is presented. Based on Monte Carlo evaluation of the system's closed-loop eigenvalues (given parameter statistics), this analysis approach introduces the probability of instability as a scalar robustness measure. The related stochastic root locus, a portrayal of the root probability density, provides insight into modal variations of the system. Parameter uncertainties may be Gaussian or non-Gaussian, bounded or not. Confidence intervals for the scalar probability of instability address computational issues inherent in Monte Carlo simulation. Appropriate confidence intervals are presented, and aids in choosing the required number of Monte Carlo evaluations are developed.

+ Ph.D. Thesis

Stochastic performance robustness measures are based on classical design criteria, as well as criteria specific to a particular application. Robust control system synthesis concepts ensue from demonstrating the ability of stochastic robustness analysis to tradeoffs in design parameters, and optimization methods suited to maximizing stochastic robustness are suggested. Four examples demonstrate aspects of the analysis, the use of confidence intervals, stability-performance tradeoffs, and synthesis through optimization. It is concluded that analysis of stochastic robustness offers a good alternative to existing robustness metrics that is inherently intuitive and precise, that is easily implemented, and that has direct bearing on engineering objectives.

9. Ray, L.R., and Stengel, R., Stochastic Performance Robustness of Aircraft Control Systems, *Proceedings of the 1990 AIAA Guidance, Navigation & Control Conference*, Portland, OR, Aug 1990, pp. 863-873.*

Stochastic robustness, a simple technique used to estimate the robustness of linear, time-invariant systems, is applied to a twin-jet transport aircraft control system. Concepts behind stochastic *stability* robustness are extended to stochastic *performance* robustness. Stochastic performance robustness measures based on classical design specifications and measures specific to aircraft handling qualities are introduced. Confidence intervals for both individual stochastic robustness measures and for comparing two measures are presented. The application of stochastic performance robustness, the use of confidence intervals, and tradeoffs between performance objectives are demonstrated by means of the twin-jet aircraft example.

10. Ray, L.R., and Stengel, R., Computer-Aided Analysis of Linear Control System Robustness, *Proceedings of the 29th IEEE Conference on Decision and Control*, Honolulu, Dec 1990, pp. 3468-3469 (To appear in *Mechatronics*).

Stochastic robustness is a simple technique used to estimate the stability and performance robustness of linear, time-invariant systems. The use of high-speed graphics workstations and control system design software in stochastic robustness analysis is discussed and demonstrated.

11. Ray, L.R., and Stengel, R., Stochastic Robustness of Linear-Time-Invariant Control Systems, *IEEE Trans. Automatic Control*, Vol. 36, No. 1, Jan 1991, pp. 82-87.**

A simple numerical procedure for estimating the stochastic robustness of a linear, time-invariant system is described. Monte Carlo evaluation of the systems' eigenvalues allows the probability of instability and the related stochastic root locus to be estimated. This analysis approach treats not only Gaussian parameter uncertainties but non-Gaussian cases, including uncertain-but-bounded variations. Confidence intervals for the scalar probability of instability address computational issues inherent in Monte Carlo simulation. Trivial extensions of the procedure admit consideration of alternate discriminants; thus, the probabilities that stipulated degrees of instability will be exceeded or that closed-loop roots will leave desirable regions also can be estimated. Results are amenable to graphical presentation.

12. Stengel, R., and Marrison, C., Robustness of Solutions to a Benchmark Control Problem, *Proceedings of the 1991 American Control Conference*, Boston, June 1991.*

The stochastic robustness of solutions to a benchmark control design problem presented at the *1990 American Control Conference* has been analyzed. The analysis quantifies the controllers' stability and performance robustness with structured uncertainties in up to six system parameters. The analysis provides insights about system response that are not readily derived from other robustness criteria, providing a common ground for judging controllers produced by alternative methods.

13. Linse, D., and Stengel, R., A System Identification Model for Adaptive Nonlinear Control, *Proceedings of the 1991 American Control Conference*, Boston, June 1991.*

A neural network model for generalized-spline function approximation in nonlinear control is described. The control system contains three elements: a nonlinear-inverse-dynamic control law that depends on a comprehensive model of the plant, a state estimator whose outputs drive the control law, and a function approximation scheme that models the system dynamics. An extended Kalman filter provides data for continuous training of the neural network during normal operation. The results of an application of the identification techniques to a nonlinear transport aircraft model are presented.